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CHANNEL WAVEGUIDE STUDY

J. M. Hammer, et al

RCA Laboratories

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Office of Naval Research  
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31 March 1975

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## CHANNEL WAVEGUIDE STUDY

J. M. Hammer, W. P. Rupp, and C. C. Yell

RCA LABORATORIES

Princeton, New Jersey 08540

31 MARCH 1975

### QUARTERLY TECHNICAL REPORT NO. 1

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  An approximate closed-form expression for the cut-off conditions and propagation characteristics of low-order modes in diffused Gaussian strip waveguides is derived. The expression is given in terms of normalized diffusion depths and strip widths and may be used to find the operating point of a LiNb <sub>x</sub> Ta <sub>1-x</sub> O <sub>3</sub> strip guide diffused from a Nb strip of known thickness and width. An experimental LiNb <sub>x</sub> Ta <sub>1-x</sub> O <sub>3</sub> "directional coupler" has been fabricated by diffusing two 5-μm-wide		

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800-Å-thick Nb strips spaced 2  $\mu\text{m}$  apart into a  $\text{LiTaO}_3$  substrate. Reasonably efficient coupling of TM modes between the strips is observed. The critical coupling length is to be estimated at 0.13 cm by fitting the data from photodensitometer measurements of a photomicrograph to the expected sine-square coupling characteristic.

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## PREFACE

This Quarterly Technical Report, prepared by RCA Laboratories, Princeton, NJ 08540, describes work performed in the Physical Electronics Research Laboratory, G. D. Cody, Director. The Project Supervisor is B. F. Williams and the Project Scientist is J. M. Hammer. Other members of the Technical Staff who participated in the research and the writing of this report are W. Phillips and C. C. Neil.

The Navy Project Monitor is T. G. Giallorenzi, Code 5500. This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by ONR under Contract No. N00014-75-C-0078.

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## I. INTRODUCTION

The work described in this report is intended to lead to the demonstration of an efficient, fast electro-optic modulator based on varying the coupling between strip waveguides on a common substrate.

We have recently demonstrated optical waveguides and electro-optic waveguide modulators using films of  $\text{LiNb}_x\text{Ta}_{1-x}\text{O}_3$  (LNT) on  $\text{LiTaO}_3$  substrates [1]. The LNT films were conceived and developed at our laboratories and show excellent waveguide and electro-optic properties. The grating modulators already made using these films have outstanding characteristics.

The method of producing these useful films is simple and essentially consists of depositing a metallic layer of niobium into a  $\text{LiTaO}_3$  substrate and then diffusing the Nb into the surface. This technique allows a variety of guiding and planar beam-forming structures to be preformed in the metallic film before diffusion. In addition, other complex configurations can be fabricated by combining sequences of metal depositions and diffusion steps.

In this program we are attempting to construct and study an electro-optically controlled strip waveguide coupling modulator capable of efficient high-speed operation.

Figure 1 is a schematic diagram of an example of the type of device we are discussing. Our intention is to provide a means of varying the amount of light coupled from guide a into guide b so that it becomes possible to couple either none of the light or any desired fraction up to 100%. In this approach, both a and b are single ( $\text{TE}_{11}$ ) mode guides.

In the interaction region of length L in Fig. 1, the two guides are brought sufficiently close so that the evanescent fields of the guides overlap in the gap "g". If the two guides have the same propagation constants, energy will be cross-coupled between them. Applying a voltage to the balanced electrodes will increase the propagation constant of one guide and decrease the propagation constant of the other, causing a phase mismatch. If the mismatch is sufficiently large, it will prevent light from coupling between the

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1. J. M. Hammer and W. Phillips, *Appl. Phys. Letters* **24**, 545 (1974).  
J. M. Hammer, M. T. Duffy, and W. Phillips, *Electro-Optic Waveguides*, Final Report, Office of Naval Research, 30 April 1974, Contract No. N00014-73-C-0388.



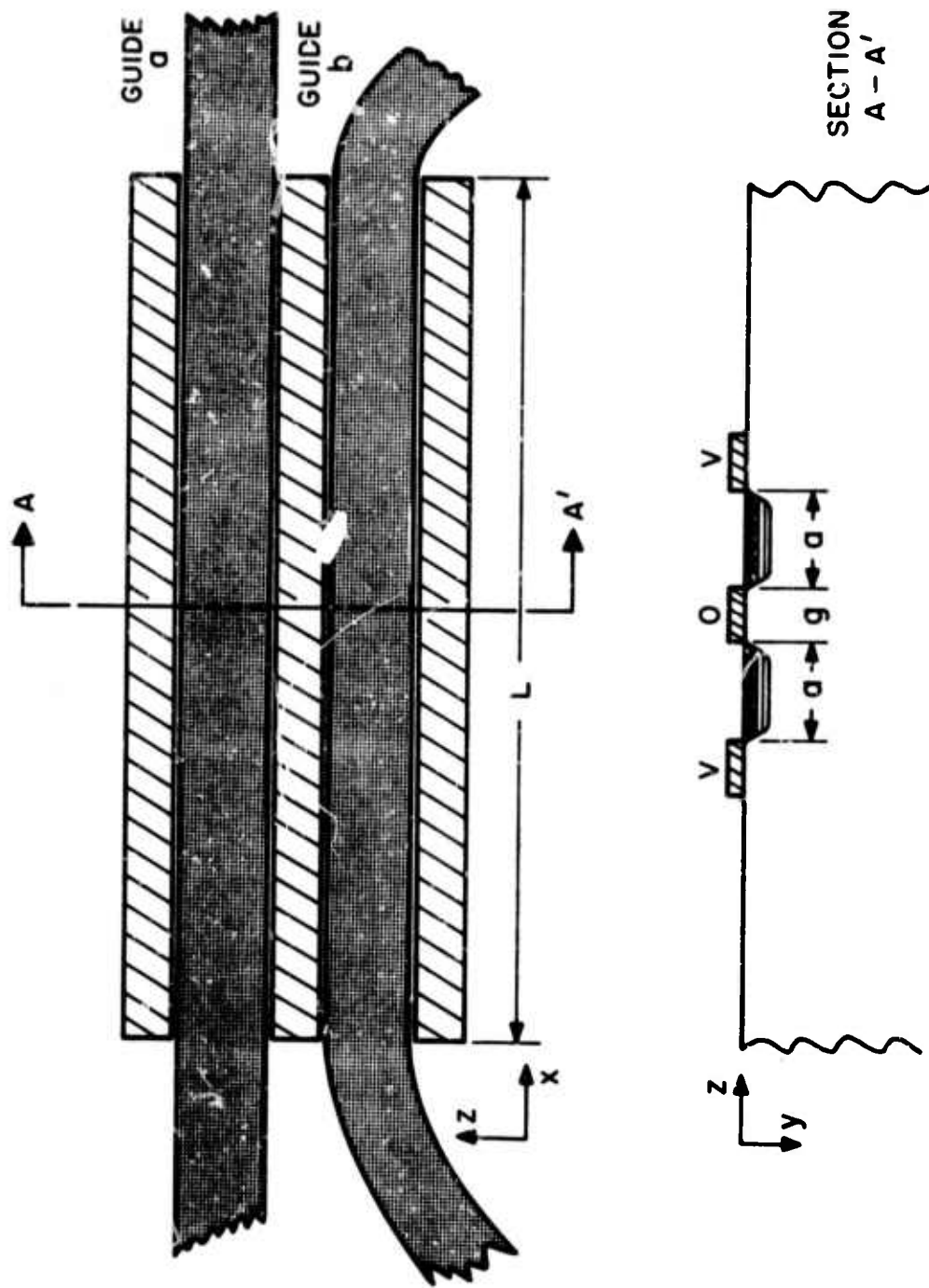


Figure 1. Schematic diagram of push-pull strip guide modulator.

guides. Near phase match the amount of light coupled per unit length will be proportional to the departure from exact match and hence to the magnitude of the voltage. Initial estimates indicate that sufficiently strong mismatch may be obtained at very low voltage ( $\sim 2$  V or less) to ensure good isolation in the off condition [2]. As with all electro-optic modulators, the speed of changing coupling will be practically limited by circuit considerations rather than by the response of the electro-optic effect. Very low drive powers ( $\lesssim 10 \mu\text{W}/\text{MHz}$ ) are expected.

In the following a refined theory of the operation of graded index strip guide is presented, and initial measurements made on an LNT strip guide coupler are described. Our work on the theory and on the fabrication and measurement of the devices is still in progress so that the results described here must be considered tentative.

To prevent unnecessary duplication of written material we assume that the reader may refer to our original proposal, which is listed as reference 2.

- 
2. RCA Proposal PP. 74-124, Channel Waveguide Study, prepared for Defense Advanced Research Projects Agency, Arlington, Va.; May 6, 1974.

## II. THEORY - Analysis of Dispersion in Diffused Strip Guides with a Gaussian Index Variation

The LNT waveguides which are used in this program have a Gaussian index variation [3]. Thus, this analysis will be based on an approximate closed-form solution for the modes of planar Gaussian index variation waveguide, which we have derived based on published solutions for waveguides with exponential refractive index grading [4,5]. This description will be briefly summarized now. By making a linear fit to the generalized dispersion curve presented by Carruthers et al. [5] the relationship

$$\sqrt{n_2 \Delta n} \quad b/\lambda_0 = 0.895 \left( \frac{\delta n}{\Delta n} + 0.167 \right) \quad (1)$$

is obtained where  $b$  is the diffusion depth. Equation (1) is a very good approximation to the dispersion of the lowest order mode of planar (one-dimensional) exponential guides over the range of index variations of interest. Figure 2 schematically shows how the index varies in a diffused strip guide. In Fig. 2,

$$\begin{aligned} \Delta n &= n_1 - n_2 \\ \delta n &= n_{\text{eff}} - n_2 \end{aligned} \quad (2)$$

where  $n_{\text{eff}}$  is defined as the effective index of the  $TE_0$  mode in the planar case ( $a \rightarrow \infty$ ). If  $\beta$  is the propagation constant for this mode,

$$\beta = 2\pi n_{\text{eff}}/\lambda_0 \quad (3)$$

$$n(y) = n_2 + \Delta n \exp(-y/b) \quad \text{Exponential} \quad (4)$$

$$n(y) = n_2 + \Delta n \exp(-(y/b)^2) \quad \text{Gaussian} \quad (5)$$

- 
3. W. Phillips and J. M. Hammer, "Formation of Lithium Niobate-Tantalate Waveguides," J. Electron. Materials. To be published May 1975. Also, Confer. on Preparation and Properties of Electronic Materials, Paper F-2; Sept. 11, 1974, Boston.
  4. E. M. Conwell, Appl. Phys. Letters 23, 328 (1973).
  5. J. B. Carruthers, I. P. Kaminow, and L. W. Stulz, Appl. Optics 13, 2333 (1974).

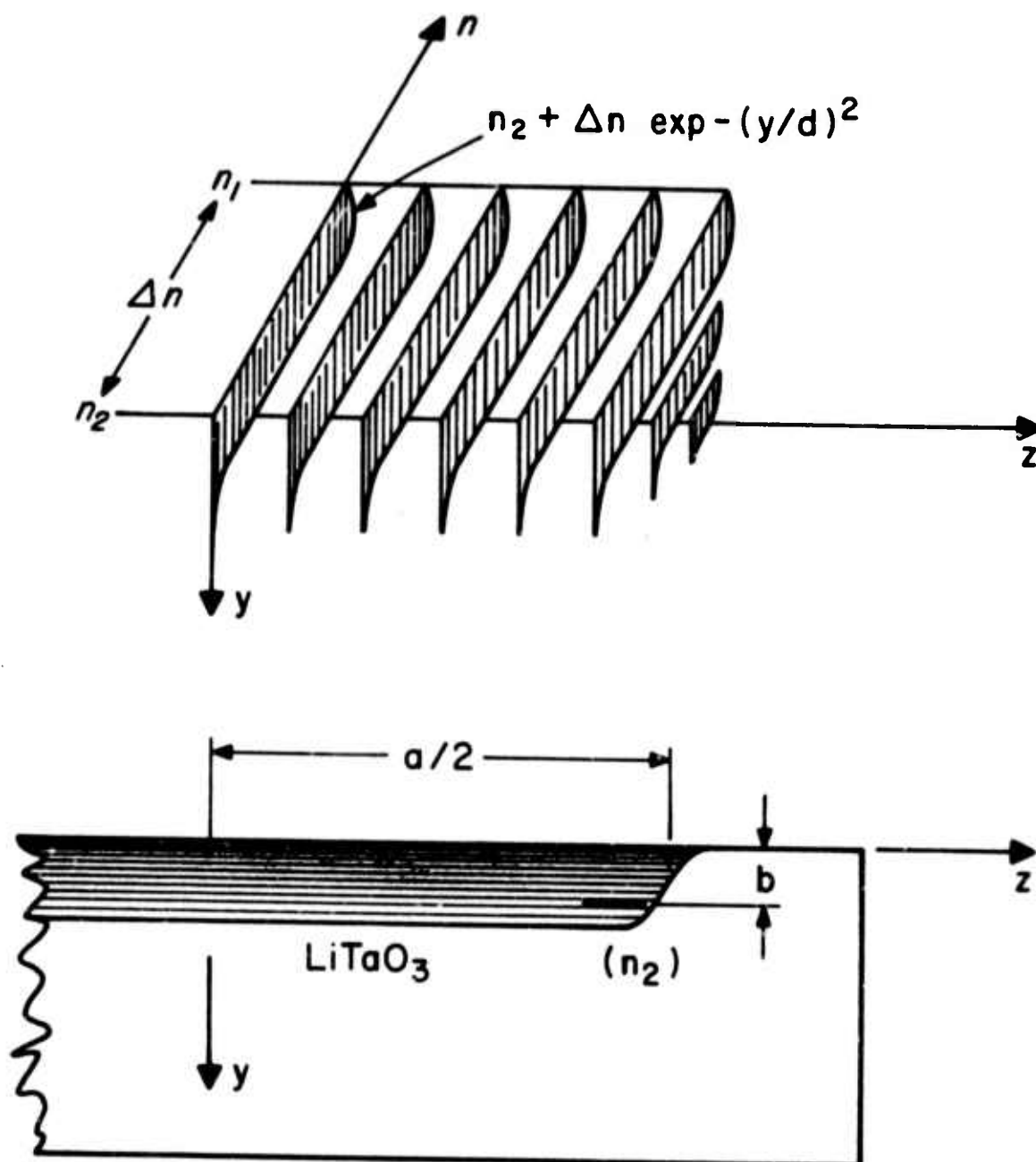


Figure 2. Representation of variation in refractive index in an LNT strip waveguide.

We find that the following substitution in Eq.(1) of the exponential theory gives good agreement with the experimentally measured dispersion of our diffused (Gaussian) waveguides.

$$\Delta n_{\text{exponential}} = 1.7 \Delta n_{\text{Gaussian}} = 1.7 \Delta n_g$$

$$b_{\text{exponential}} = 2 b_{\text{Gaussian}} = 2 b_g$$

With this substitution, Eq.(1) becomes

$$\sqrt{n_2 \Delta n_g} \ b_g / \lambda_o = 0.807 \left( \frac{\delta n}{\Delta n_g} + 0.284 \right) \quad (6)$$

The values predicted using Eq.(6) agree closely with the results of a computer calculation for Gaussian waveguides recently reported by Hocker and Burns [6]. The  $TE_0$  cut-off condition for planar Gaussian guides is obtained from Eq.(6) by setting  $\delta n = 0$ .

As will be seen below, generalized relations can be obtained by using normalized dimensions. Define the normalized diffusion depth or guide thickness as

$$B_g = \sqrt{n_2 \Delta n_g} \ b_g / \lambda_o \quad (7)$$

Then Eq.(6) becomes

$$\left( \frac{\delta n}{\Delta n_g} \right) = \frac{B_g}{0.807} - 0.284 \quad (8)$$

Marcatili [7] has analyzed channel or strip guides with step index variation. He gives an approximate closed-form solution to the dispersion in step index channel guides. Marcatili's approximation seems to be valid over the range of

- 
- 6. G. B. Hocker and W. K. Burns, IEEE J. Quantum Electronics, to be published.
  - 7. E. A. J. Marcatili, Bell Syst. Tech. J. 48, 2071 (1969).

$\Delta n$ 's with which we are concerned here. We may write his approximate solution as

$$\left(\frac{\delta n}{\Delta n_s}\right)_{qp} = 1 - \frac{p^2/8}{\left(A_s + \frac{1}{\pi\sqrt{2}}\right)^2} - \frac{q^2/8}{\left[B_s + \frac{1}{2\pi}\left(\sqrt{\frac{n_2\Delta n_s}{n_2^2-1}} + \frac{1}{\sqrt{2}}\right)\right]^2} \quad (9)$$

where  $A_s$  is the normalized strip or channel width given by

$$A_s = \sqrt{n_2\Delta n_s} \quad a_s/\lambda_0 \quad (10)$$

Here the subscript  $s$  is used to identify quantities associated with step index variation guides. Equation (9) gives the dispersion of the  $TE_{qp}$  mode of a strip guide with a step index variation.

We now adopt the strategy of finding the thickness  $b_s$  of a planar step index guide, which gives the same value of  $\delta n$  as a planar Gaussian index guide of depth  $b_g$  when  $\Delta n_s$  is taken equal to  $\Delta n_g$  and  $(n_2)_g = (n_2)_s$ . We will then substitute  $B_g$  for  $B_s$  in Eq. (9) to find an approximate dispersion for a Gaussian strip guide.

As our first step in this procedure, let the width of the strip become infinite. Thus, we let  $a, A \rightarrow \infty$  in Eq. (9), which now describes the dispersion for a planar step index guide. Since we are concerned only with the lowest mode, we take  $p = q = 1$ . (Note that as  $a \rightarrow \infty$ ,  $TE_{11} \rightarrow TE_0$  [2].) We obtain, equating the right side of Eq. (8) to that of Eq. (9) under the conditions cited above,

$$B_s = \frac{1}{\sqrt{8\left(1.284 - \frac{B_g}{0.807}\right)}} - \frac{1}{2\pi}\left(\sqrt{\frac{n_2\Delta n}{n_2^2-1}} + \frac{1}{\sqrt{2}}\right) \quad (11)$$

The subscript is dropped from  $\Delta n$  because, as mentioned earlier,  $\Delta n_s$  is chosen equal to  $\Delta n_g$ .

The two-dimensional guides of interest in this program will have widths (a) at least five times larger than their depths (b). Thus, little error would be expected in using the step index approach to describe the reflections at the strip edge as compared with using the step index approach to describe the reflections at the broad interface (see Fig. 2). We will thus use the "A"



term of Eq.(9) without essential modification except as indicated below and will substitute from Eq.(11) for the "B" term. We thus obtain the approximate dispersion relation

$$\left(\frac{\delta n}{\Delta n}\right)_{qp} = 1 - \frac{p^2}{8\left(A + \frac{1}{\pi\sqrt{2}}\right)^2} - q^2(1.284 - B/0.807) \quad (12)$$

The subscripts have now been dropped. Note that B is to be taken as the normalized Gaussian depth and A as the normalized strip width after diffusion. If  $a_1$  is the width of the Nb strip before diffusion, the width a after diffusion will be taken as

$$a = a_1 + 2(b/2) \quad (13)$$

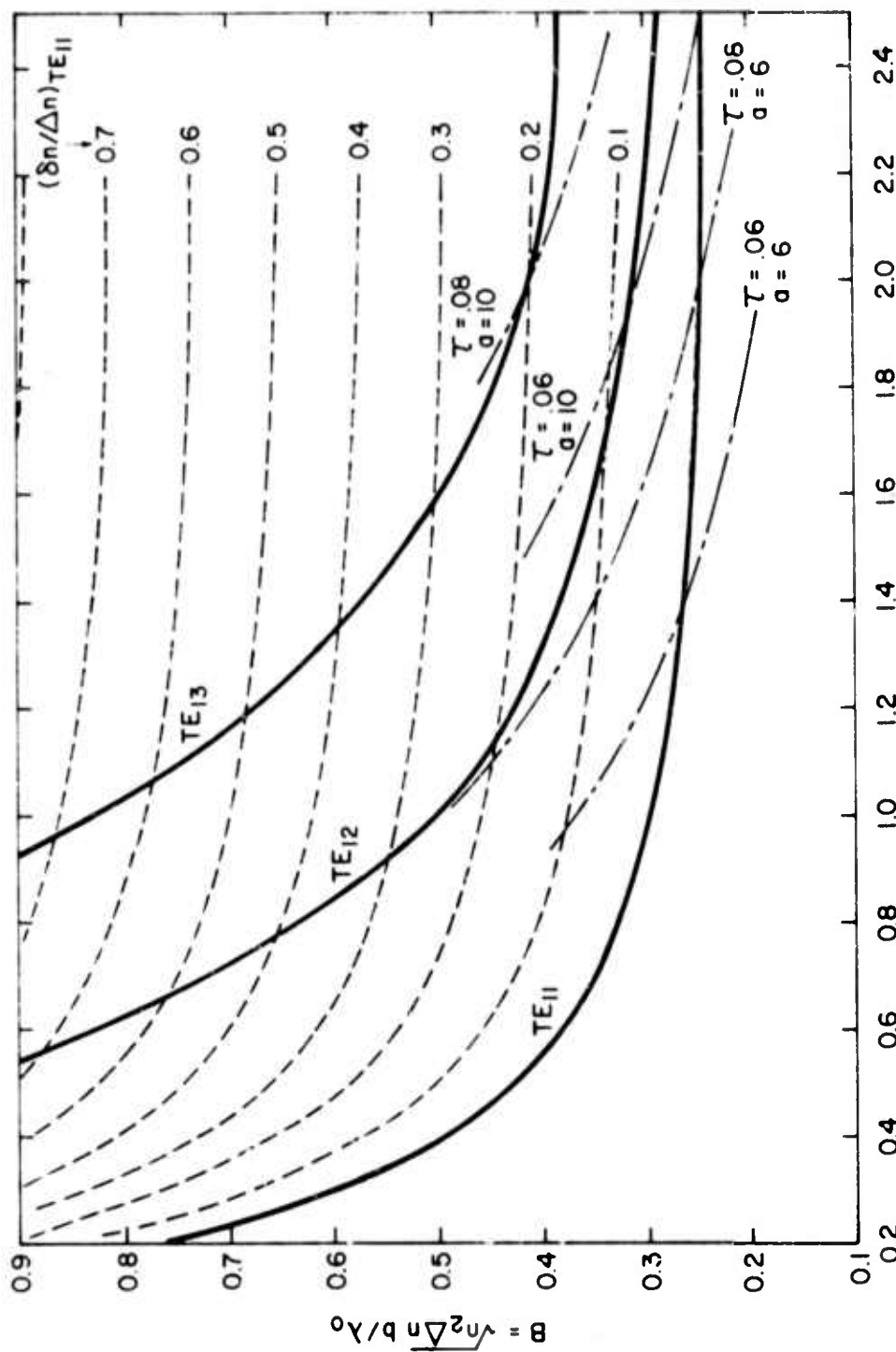
We expect Eq.(12) to be reasonably accurate for the  $TE_{1p}$  modes and, for relatively weak guides, also to represent the  $TM_{1p}$  modes. This latter feature will be discussed further in the next quarterly report. The  $TE_{qp}$  modes with  $q \geq 2$  will not be well described by Eq.(12). We expect highest accuracy for the  $TE_{11}$ ,  $TM_{11}$  modes, which are the ones of greatest concern. It should be remembered that the values of  $n_2$ ,  $\Delta n$  used must always be those appropriate to the polarization and orientation directions being considered [1].

Mode cut-off is obtained by setting  $\delta n = 0$  in Eq.(12). Values of A as a function of B for the  $TE_{11}$ ,  $TE_{12}$ ,  $TE_{13}$  cut-off conditions are plotted as the solid curves in Fig. 3. The family of curves A vs B with  $\delta n/\Delta n$  as parameter for the  $TE_{11}$  is plotted as the dotted curves in Fig. 3.

From our studies of the formation of planar LNT waveguides the relationship of diffusion depth, initial thickness of metallic niobium  $\tau$ , and  $\Delta n$  has been found [3]. For y-plates, these are (at  $\lambda_0 = 0.6328 \mu m$ )

$$\begin{array}{l} \text{TE} \\ \text{Modes} \end{array} \left\{ \begin{array}{ll} \Delta n = 0.383 \tau/b & \text{propagation parallel to c-axis} \\ \Delta n = 0.188 \tau/b & \text{propagation at } 51^\circ \text{ to c-axis} \\ \Delta n = 0.0682 \tau/b & \text{propagation perpendicular to c-axis} \end{array} \right. \quad (14)$$

$$\begin{array}{l} \text{TM} \\ \text{Modes} \end{array} \quad \Delta n = 0.383 \tau/b \quad \text{any direction on plane} \quad (15)$$



$$A = \sqrt{n_2 \Delta n} a / \lambda_0$$

Figure 3. Normalized strip width  $A = \sqrt{n_2 \Delta n} a / \lambda_0$  vs normalized diffusion depth (thickness)  $B = \sqrt{n_2 \Delta n} b / \lambda_0$ . Solid curves cut-off limits  $TE_{11}$ ,  $TE_{12}$ ,  $TE_{13}$  ( $\delta n = 0$ ). Dotted curves  $A$  vs  $B$  for  $TE_{11}$  mode with  $\delta n / \Delta n$  as parameter and values as labeled. Dash-dot curves range of  $A$  and  $B$  as  $b$  is varied for values of initial Nb thickness  $\tau$  and strip width  $a$  as labeled. These curves may also be used for TM modes.

The diffusion depth  $b$  may be found from the temperature and time of diffusion [3]. For a given strip width and initial niobium thickness, Eqs.(14) and (15) allow the normalized thickness  $B$  and width  $A$  to be directly calculated as a function of  $b$ .

Taking propagation of a TE mode at  $51^\circ$  to the  $c$ -axis in a  $y$ -plate we have calculated  $A$  and  $B$  as  $b$  is varied from 0.6 to 2.5  $\mu\text{m}$  for the values (in  $\mu\text{m}$ ):  $\tau = 0.08$ ,  $a = 6$ ;  $\tau = 0.08$ ,  $a = 10$ ;  $\tau = 0.06$ ,  $a = 6$ ; and  $\tau = 0.06$ ,  $a = 10$ . The curves of  $A$  vs  $B$  for these cases are shown in Fig. 3 as dot-dash lines. These curves can be conveniently used to select an operating point. Operating points for other directions can, of course, be calculated directly, using Eqs.(14) and (15) as needed.

We should note that the cut-off curves given in the contract proposal [2] were derived under very restricted conditions before the propagation characteristics of the LNT guides were fully characterized and are inaccurate.

We are continuing our theoretical study and directing our efforts to obtain an accurate calculation of the coupling coefficients and voltage behavior when the strip guides are arranged as directional couplers.

### III. EXPERIMENTAL MEASUREMENTS

Initial efforts have been directed to the production of coupling modulators using conventional photoresist techniques. A dimensioned schematic of the first mask used is shown in Fig. 4. The initial experimental structure was formed on a polished  $\gamma$ -plate of  $\text{LiTaO}_3$  using conventional photolithography as follows: 800 Å of Nb is deposited by e-beam evaporation; Shipley AZ1350 photoresist is spun over the Nb, exposed through the mask, and developed. The Nb is then etched using a mixture of one part buffered HF to one part concentrated  $\text{HNO}_3$  at room temperature. A photomicrograph of the input section of the Nb pattern before diffusion is shown in Fig. 5. The entry horn for the upper strip guide is seen on the left. The abrupt termination of the lower strip guide should also be noted. The Nb is diffused for 2 hr 10 min at  $1185^\circ\text{C}$ , giving a diffusion depth of  $1.2\text{ }\mu\text{m}$ . Figure 6 is a photomicrograph of the coupler after diffusion. The gap between the guides is still clearly visible, but it is not possible to determine if the index in the gap region is depressed to the substrate value or not. Starting with an initial  $2\text{-}\mu\text{m}$  gap in the Nb, some overlap would be expected after diffusion.

The guides in this first experiment were placed to run at right angles to the  $c$ -axis of the substrate. For the values used at  $\lambda_0 = 0.6328\text{ }\mu\text{m}$  the TE mode would be expected to be cut off for propagation perpendicular to the  $c$ -axis. The TM mode, however, will propagate. This may be seen by noting that from Eq. (14)  $\Delta n = 0.00455$ , giving  $B = 0.189$ . It is clear from Fig. 3 that this value of  $B$  is below cut-off for any  $A$ . For TM propagation, however,  $\Delta n = 0.0255$ ,  $B = 0.447$ , and  $A = 2.23$ , which will propagate the  $\text{TM}_{11}$ ,  $\text{TM}_{12}$ , and  $\text{TM}_{13}$  modes.

To observe operation as a directional coupler, light is coupled into the horn of the upper guide with a  $\text{SrTiO}_3$  prism coupler. We then observe light emerging from the horn of the lower guide on the right. Figure 7 is a low-magnification photograph of the coupler in operation.

When an output coupling prism is placed on the horn of the lower guide, light is coupled out. The ratio of light emerging from the output prism to light entering the input prism is 0.29, which is a very gratifying transmission. The emergent light contains a mixture of TE and TM polarization directions. The degree of admixture is sensitive to the pressure applied to the coupling



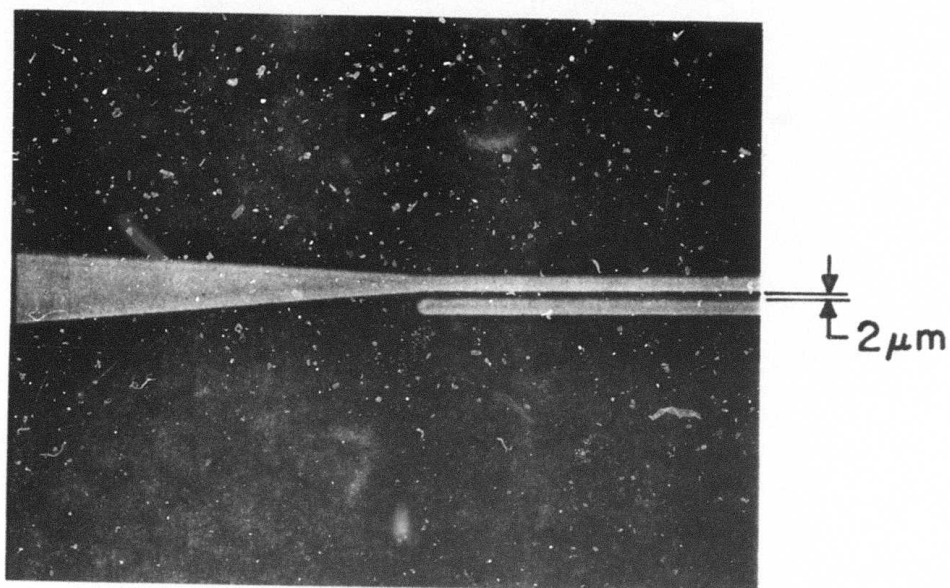


Figure 5. Photomicrograph of Nb pattern to form coupler deposited on  $\text{LiTaO}_3$  substrate before diffusion. Nb thickness  $\tau = 0.08 \mu\text{m}$ .

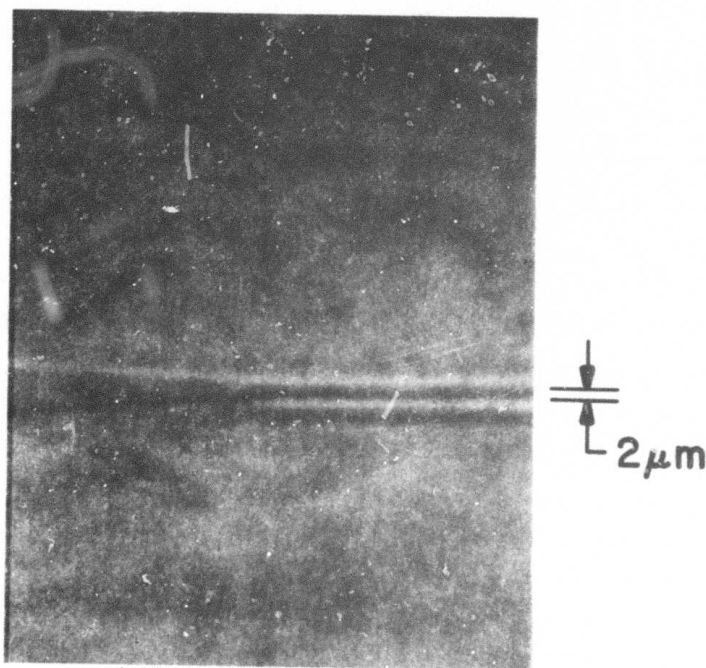


Figure 6. Photomicrograph of coupler after diffusion at  $1185^\circ\text{C}$  for 2 hr 10 min.





Figure 7. Low-magnification photograph of 6328-Å light coupled into upper strip. Prism coupler on left couples light into entry horn for upper strip. Light emerges from lower strip horn on right and is reflected at broken edge of sample, which intersects the lower horn.

prism and does not vary strongly as the input polarization direction is varied from TE to TM. This effect requires further study, but we tentatively conclude that the light transmitted and directionally coupled between the two strip guides is in the TM mode and the admixture of apparent TE-TM is due to stress birefringence at the coupling prisms.

In order to check the coupling length a photomicrograph of the scattered light from the strips is taken using a long-focal-length objective, which gives a scale factor on the photograph of 100  $\mu\text{m}$  per cm. The photograph is shown in Fig. 8. Photodensitometer scans across the streaks are taken at 4-mm intervals along the propagation direction, which corresponds to 40- $\mu\text{m}$  intervals on the actual guide. The relative intensity  $I_a(I_a + I_b)$  is plotted in Fig. 9. These data are fitted to a  $\sin^2 kX$  function, giving a critical coupling length  $L = \pi/2k = 0.13$  cm.

We thus have observed efficient directional coupling between two strip LNT waveguides. Additional guides are in preparation. In these new couplers the gap and the orientation will be varied in order to further investigate and control the coupling characteristics. Photomasks for the deposition of

electrodes have also been prepared and will be used to deposit electrodes on a suitable directional coupler.

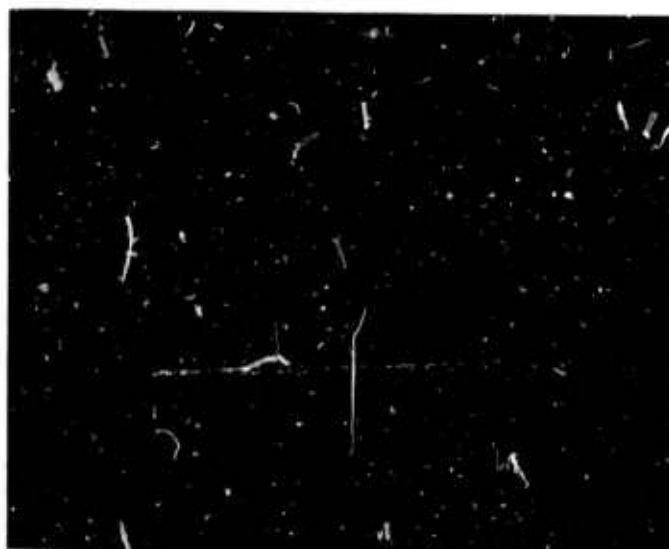


Figure 8. High-magnification photograph of portion of directional coupler. 1 cm on photograph corresponds to 100  $\mu\text{m}$  on sample. The intensity of the light traveling from left to right in upper strip diminishes. The intensity of the light in lower strip increases from left to right.

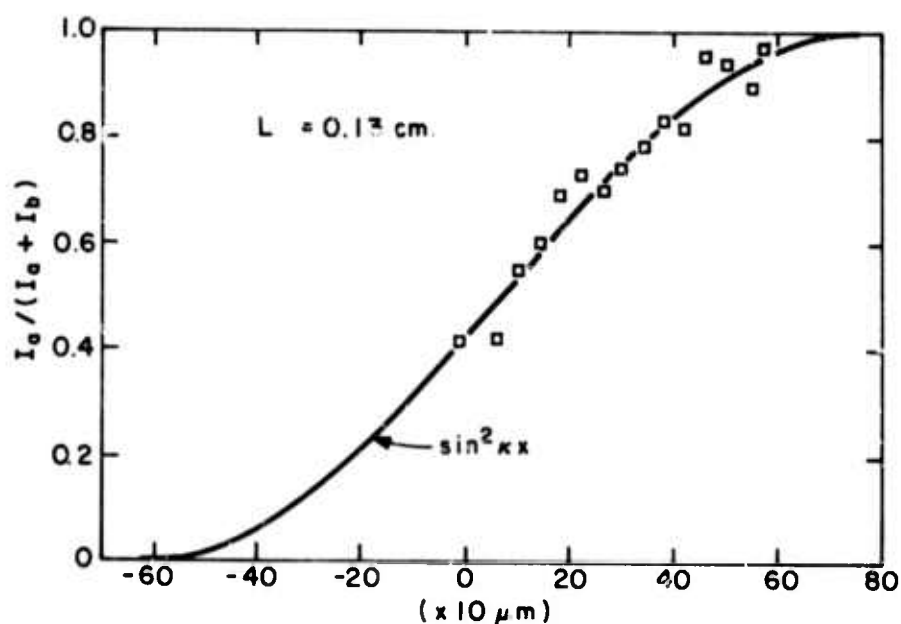


Figure 9. Data points - normalized values of photodensitometer scans across coupler taken on copy of Fig. 8. Solid curve fitted to  $\sin^2 kx$  plot.

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